

# *Theory Overview*

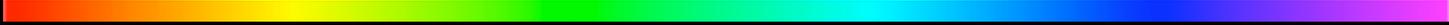


Hitoshi Murayama

LBNLnu

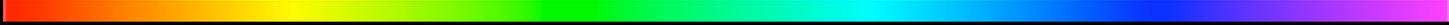
September 4, 2002

# *Disclaimer*



- Discussion today is limited to “neutrino properties”
- Not covered:
  - High-energy neutrino astronomy
  - Indirect dark matter search
  - solar neutrino astrophysics
  - Supernova neutrinos
  - GZK neutrinos
  - cosmic relic neutrinos
- Try to raise some points for debate

# Outline



- Introduction
- Current Status of Neutrino Oscillation
- Future – LSND false –
  - LMA true
  - LMA false
- Future – LSND true –
- Absolute Mass Scale
- Majorana vs Dirac
- Conclusion

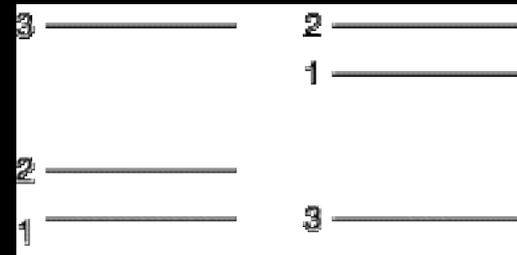
# *Current Status of Neutrino Oscillation*



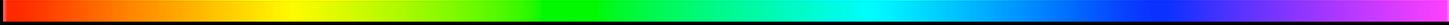


# Three-generation

- Solar & atmospheric  $\theta$  oscillations easily accommodated within three generations
- $\sin^2 2\theta_{23}$  near maximal,  $\Delta m^2_{\text{atm}} \sim 3 \times 10^{-3} \text{eV}^2$
- $\sin^2 2\theta_{12}$  large,  $\Delta m^2_{\text{solar}} \sim 3-30 \times 10^{-5} \text{eV}^2$ ?
- $\sin^2 2\theta_{13} < 0.05$  from CHOOZ, Palo Verde
- Because of small  $\sin^2 2\theta_{13}$ , solar & atmospheric  $\theta$  oscillations almost decouple
- Need to know the solar situation,  $\sin^2 2\theta_{13}$ , and mass hierarchy



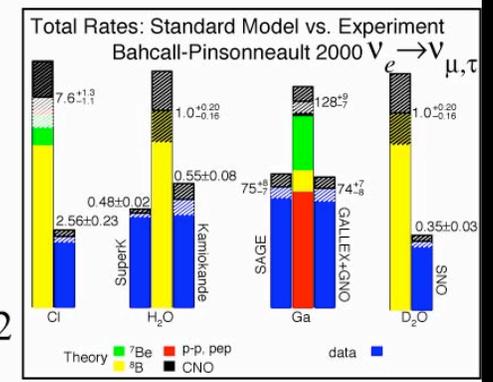
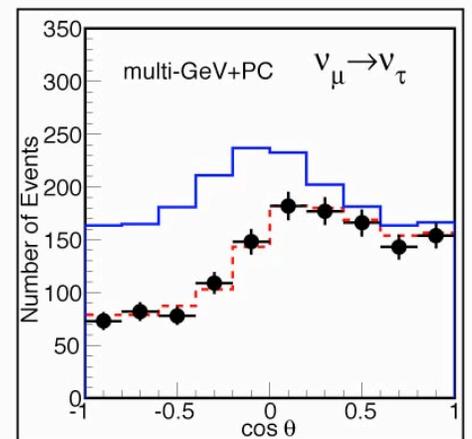
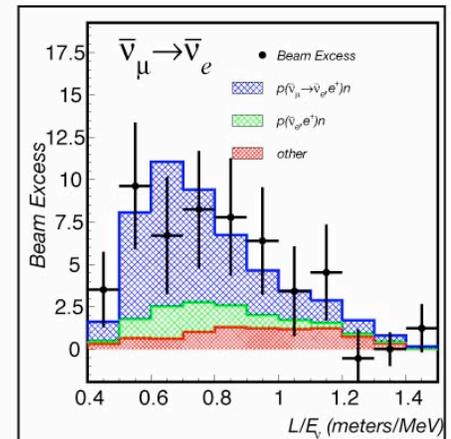
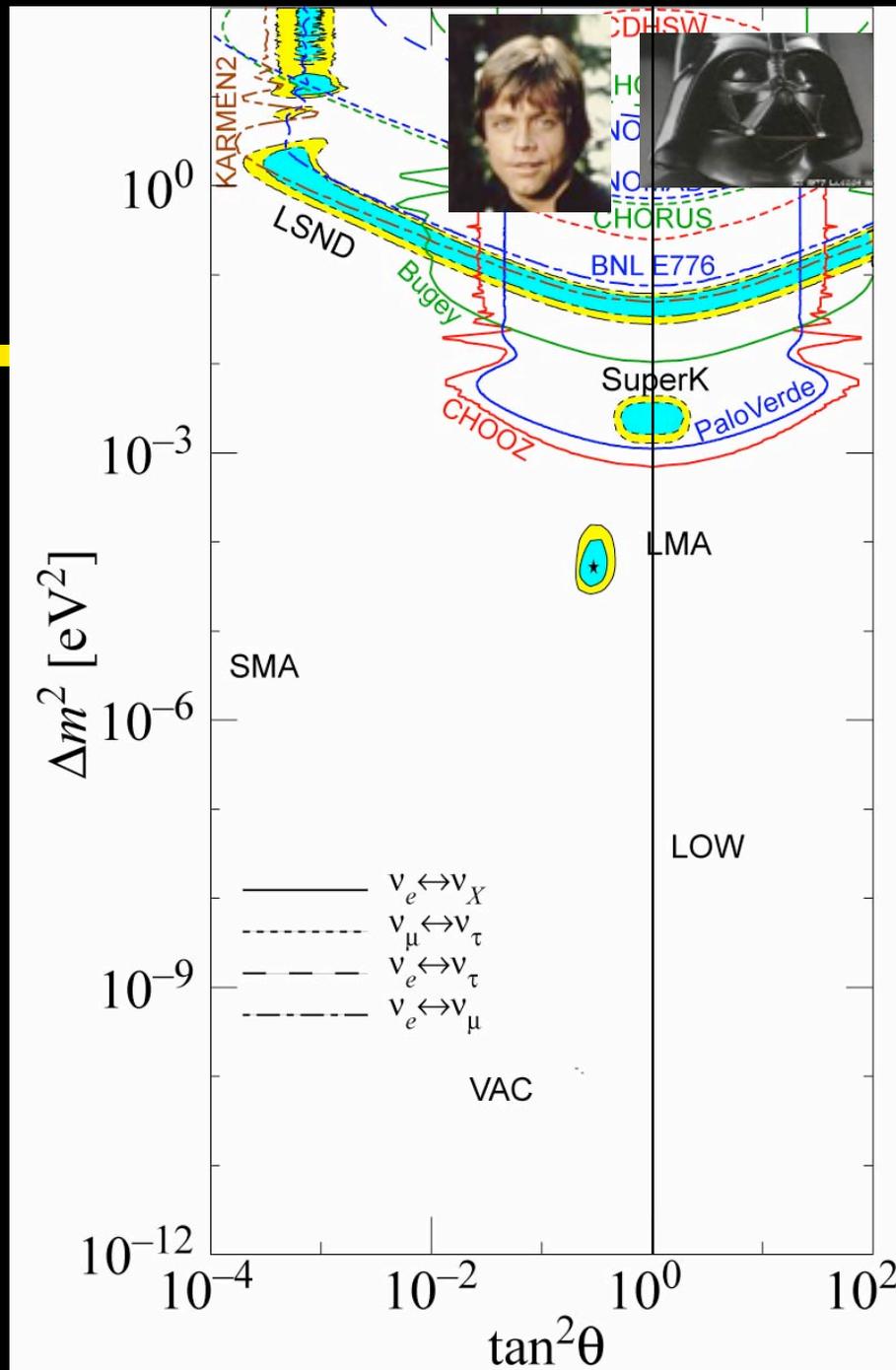
# *What we learned in 2001–2*



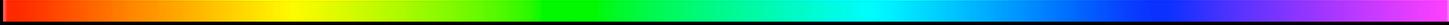
- Atmospheric  $\bar{\nu}_\mu$  is lost ( $>10\%$ ), converted mostly likely to  $\bar{\nu}_\tau$  ( $>99\%$ CL) (SK, MACRO)
- Solar  $\bar{\nu}_e$  is converted to either  $\bar{\nu}_\mu$  or  $\bar{\nu}_\tau$  ( $>5\%$ ) (SNO)
- Explanation is probably neutrino oscillation
  - Other possibilities: Neutrino decay, Violation of equivalence principle, spin resonant rotation, FCNC
  - Possible, but models tend to be ugly
- Tiny neutrino mass: the first evidence for *incompleteness of Minimal Standard Model*

March 2002

April 2002  
with SNO



# *Typical Theorists' View ca. 1990*



- Solar neutrino solution *must* be small angle MSW solution because it's cute *Most likely wrong!*
- Natural scale for  $\Delta m^2_{23} \sim 10\text{--}100 \text{ eV}^2$  because it is cosmologically interesting *Wrong!*
- Angle  $\theta_{23}$  must be of the order of  $V_{cb}$  *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle *Wrong!*

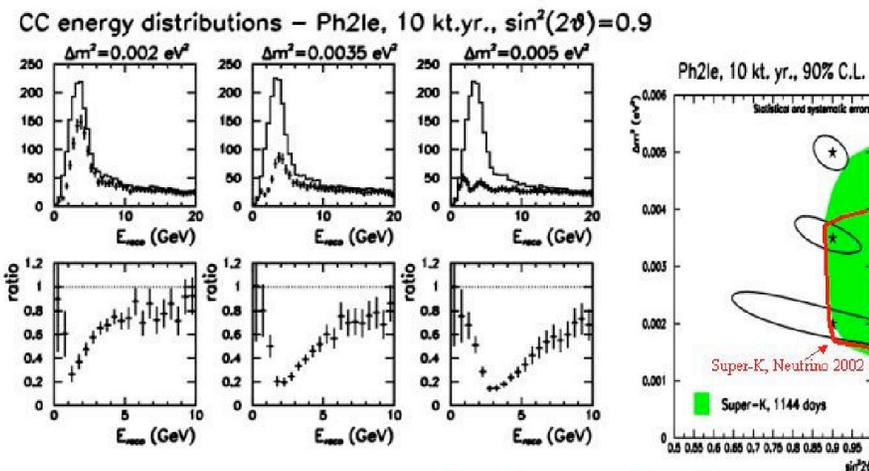
# MINOS (NuMI)

## OPERA/ICARUS (CNGS)

- MINOS: precision measurements of  $(\Delta m_{23}^2, \sin^2 2\theta_{23})$

- OPERA/ICARUS @ CNGS: tau appearance in  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$
- Limited consistency check that there is no  $\bar{\nu}_\mu \rightarrow \nu_s$  with large error

### Measurement of Oscillations in MINOS



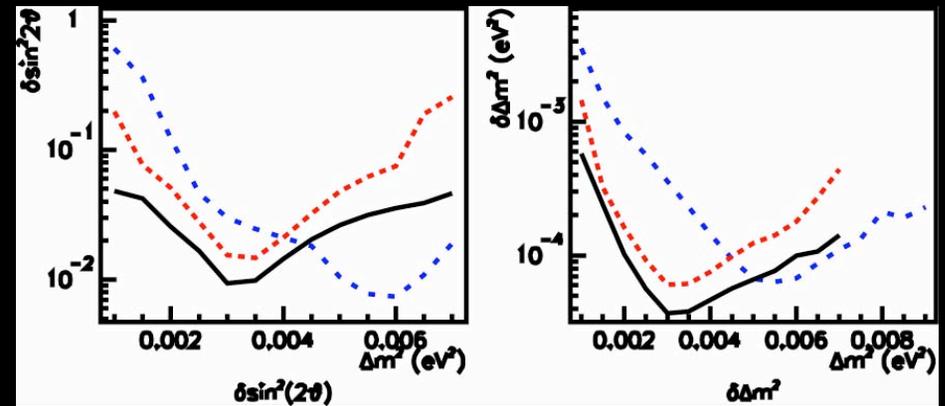
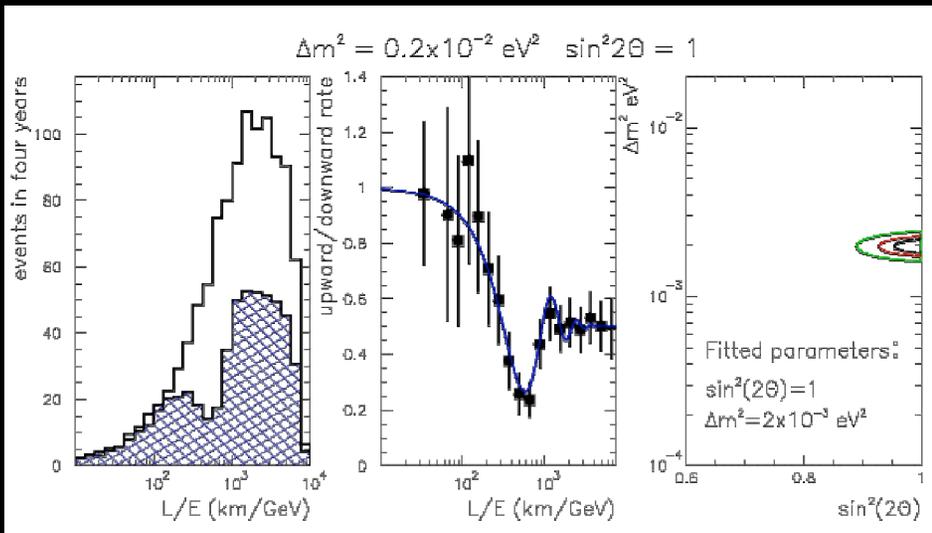
Note: MINOS beam results are presented for only 2 years of running! Longer-term running is certainly possible, even probable. Results are statistics limited.

$\Delta m_{23}^2$	1.2	2.4	5.4	BG
$\Delta m_{23}^2 / 10^{-3} \text{eV}^2$				
OPERA	2.7	10.8	53.5	0.75
5 years				

# MONOLITH, JHF2K

- MONOLITH aims at verifying oscillation curves with atmospheric neutrinos

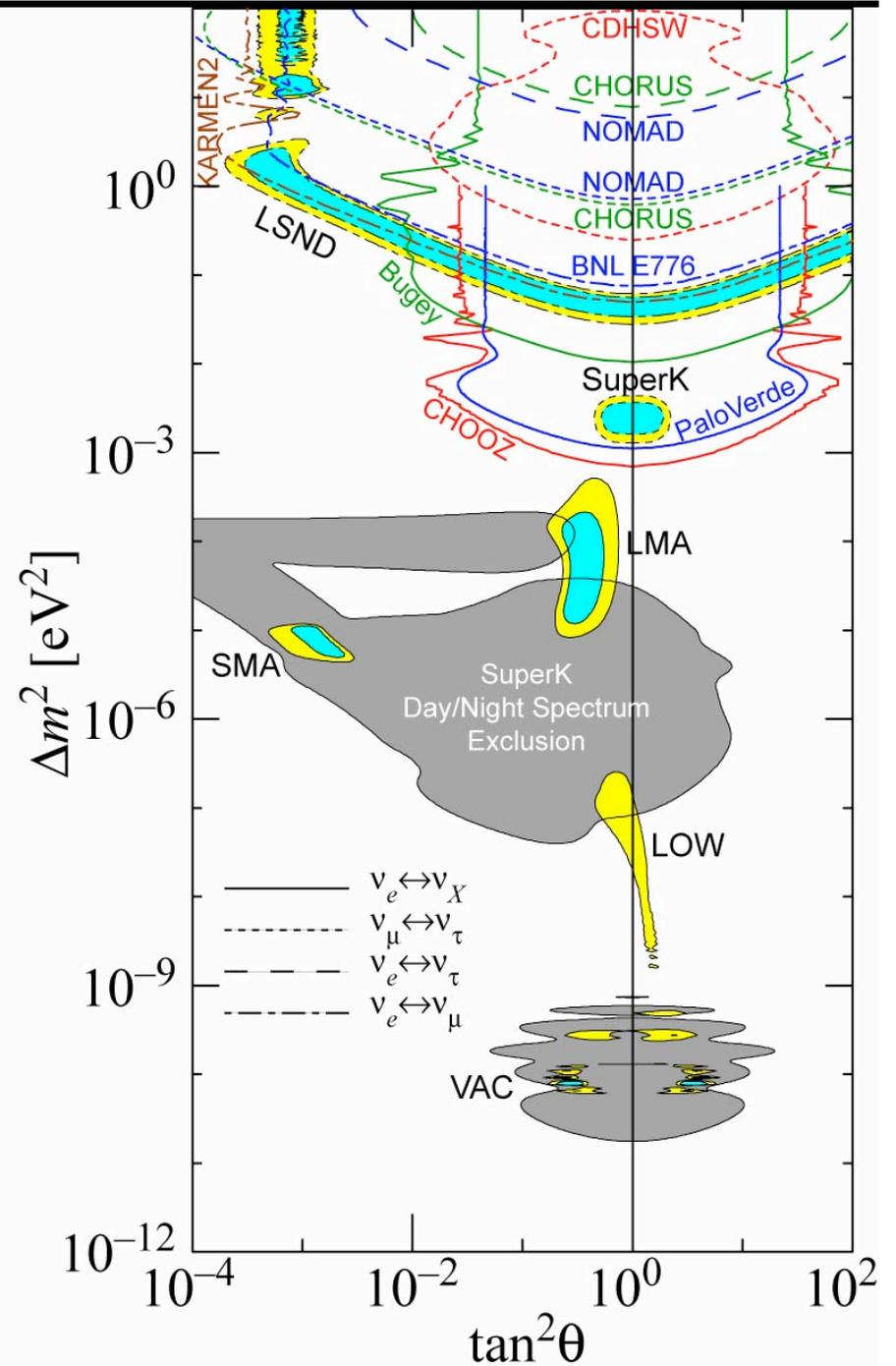
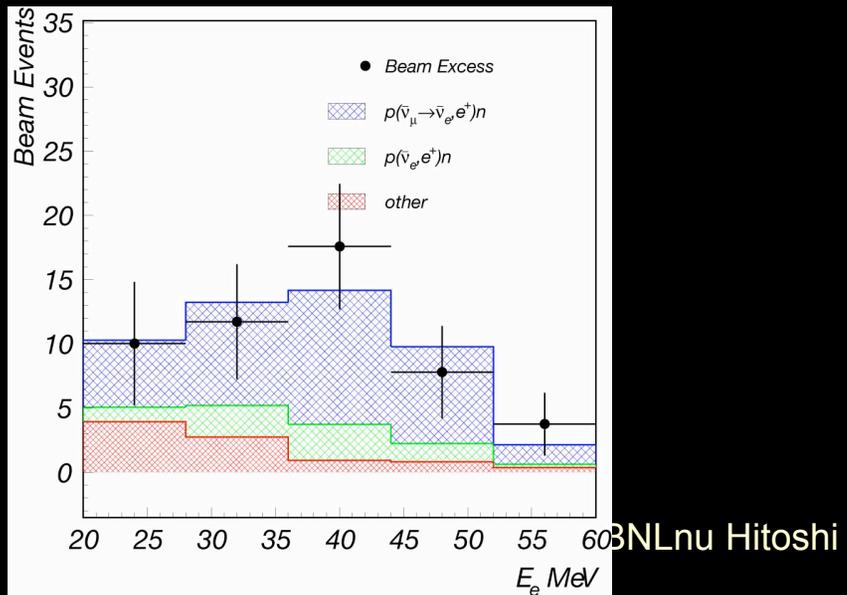
- JHF2K: Further precision measurements of  $\Delta m^2_{23}, \sin^2 2\theta_{23}$



# LSND 3.3

- Excess positron events over calculated BG

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e e^+) = (0.264 \pm 0.067 \pm 0.045)\%$$



# Sterile Neutrino

- **LSND**, atmospheric and solar neutrino oscillation signals

$$\square m_{\text{LSND}}^2 \sim \text{eV}^2$$

$$\square m_{\text{atm}}^2 \sim 3 \times 10^{-3} \text{eV}^2$$

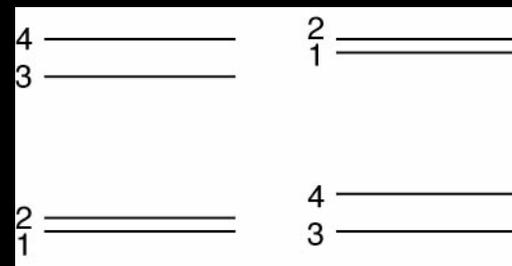
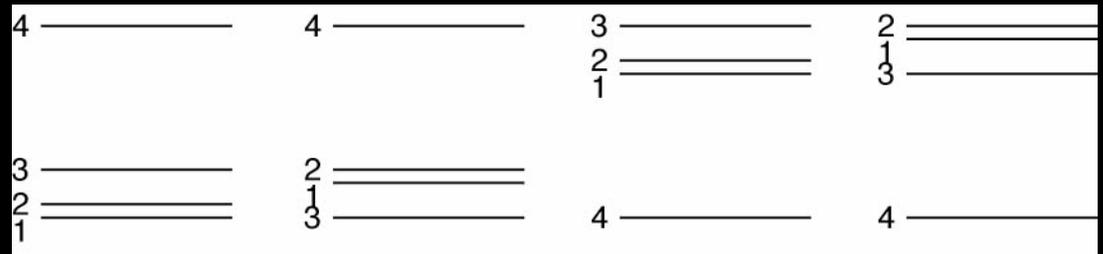
$$\square m_{\text{solar}}^2 < 10^{-3} \text{eV}^2$$

Can't be accommodated with 3 neutrinos

Need a *sterile neutrino*

*New type of neutrino with no weak interaction*

- 3+1 or 2+2 spectrum?



# *Sterile Neutrino getting tight*

- 3+1 spectrum:  $\sin^2 2\theta_{\text{LSND}} = 4|U_{4e}|^2|U_{4\mu}|^2$ 
    - $|U_{4\mu}|^2$  can't be big because of CDHS, SK U/D
    - $|U_{4e}|^2$  can't be big because of Bugey
    - Marginally allowed (90% excl. vs 99% allw'd)
  - 2+2 spectrum: past fits preferred
    - Atmospheric mostly  $\nu_\mu \leftrightarrow \nu_\tau$
    - Solar mostly  $\nu_e \leftrightarrow \nu_s$  (or vice versa)
    - Now solar sterile getting tight due to SNO  
(Barger et al, Giunti et al, Gonzalez-Garcia et al, Strumia)
- *Both scenarios disfavored at ~99% CL*

# *CPT Violation?*

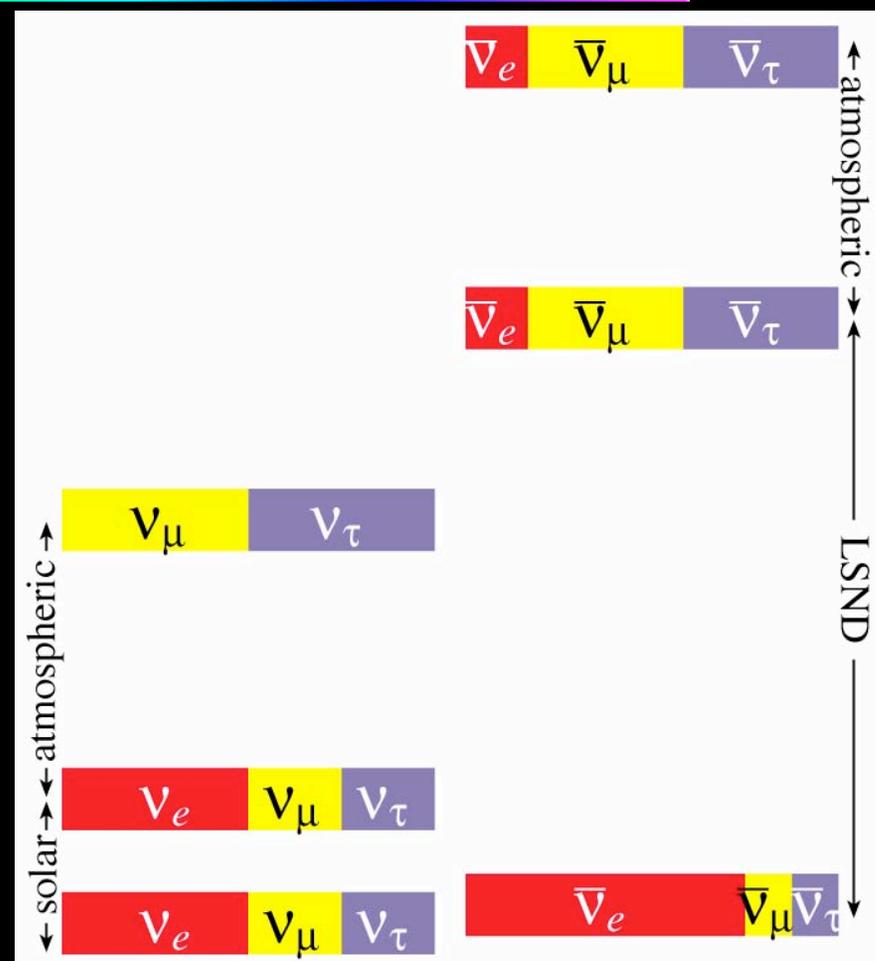
## *“A desperate remedy...”*

- LSND evidence:  
*anti-neutrinos*
- Solar evidence:  
*neutrinos*
- If neutrinos and anti-neutrinos have different mass spectra, atmospheric, solar, LSND accommodated without a sterile neutrino

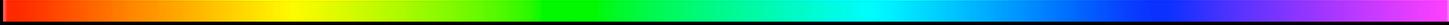
(HM, Yanagida)

*Best fit to current data*

(Strumia)



# *Pressing Questions*



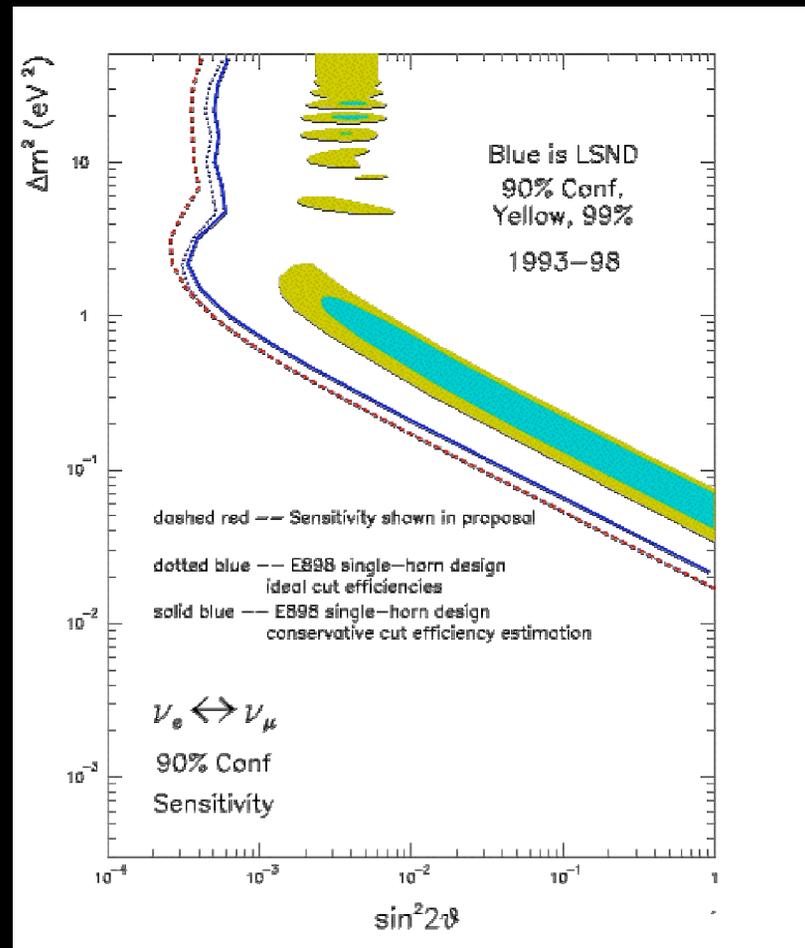
- Solution to the solar neutrino problem?
- How small is  $\Delta_{13}$ ?
- Mass hierarchy?
- CP Violation?
- LSND? Sterile neutrino(s)? CPT violation?
- Absolute mass scale?
- Dirac or Majorana?

*Future*  
– *LSND false* –



# Mini-BooNE

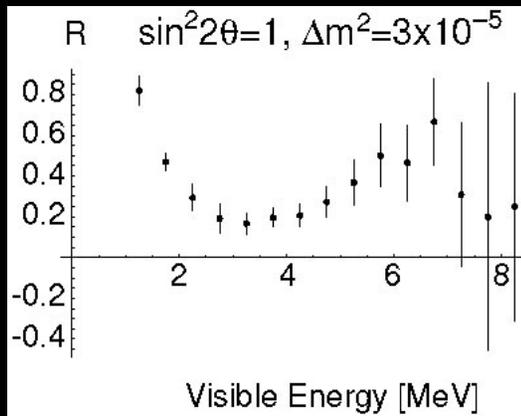
- Settles the issue of LSND evidence
- Major branch point: do we need a sterile neutrino? CPT violation?
- Suppose LSND disproven by Mini-BooNE



# KamLAND

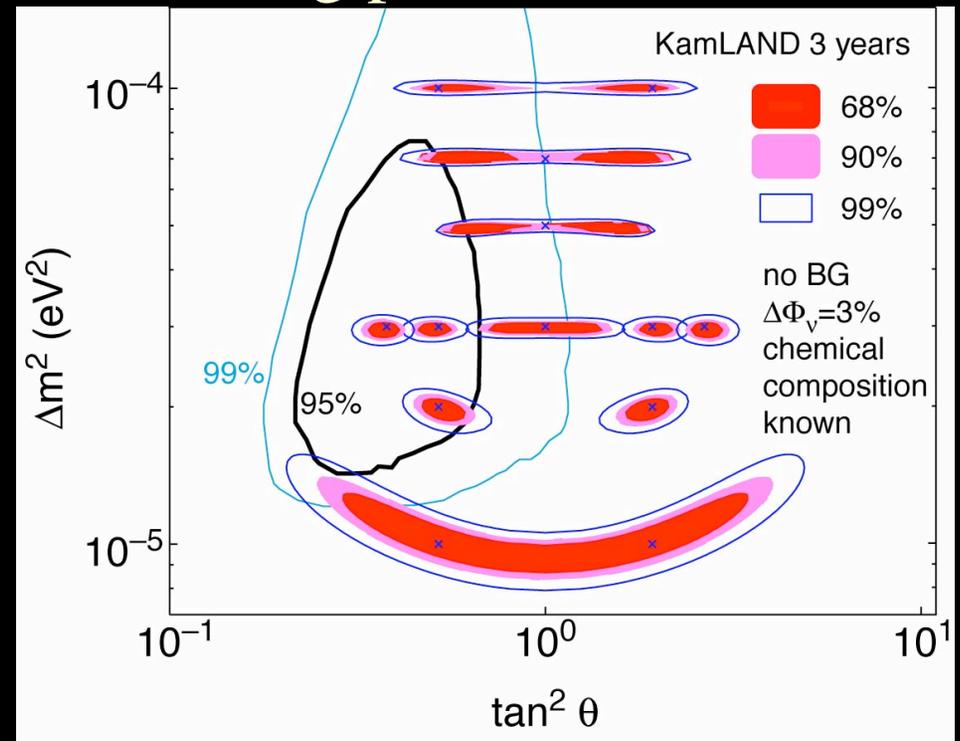
- Can see the **dip** when  $\Delta m^2 > 2 \times 10^{-5} \text{eV}^2$

(Pierce, HM)



Data/theory

- Can measure mass & mixing parameters



# *Mini-KamLAND*



- If  $\Delta m^2 > 10^{-4} \text{eV}^2$ , oscillation washed out at KamLAND
- Need “Mini-KamLAND” with  $L \sim 20 \text{km}$  to measure  $\Delta m^2$  (hep-ex/0203013)

## *If LMA confirmed...*



- Dream case for neutrino oscillation physics!
- $\Delta m^2_{\text{solar}}$  within reach of long-baseline expts
- Even CP violation may be probable
  - neutrino superbeam
  - muon-storage ring neutrino factory
- If LMA excluded by KamLAND, study of lower energy solar neutrinos crucial

# CP Violation

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 16s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin\delta \sin\frac{\Delta m_{12}^2 L}{4E} L \sin\frac{\Delta m_{13}^2 L}{4E} L \sin\frac{\Delta m_{23}^2 L}{4E} L$$

- Possible only if:
  - $\Delta m_{12}^2, s_{12}$  large enough (LMA)
  - $\delta_{13}$  large enough

# *superbeam*

- Existing proposals of neutrino superbeam

(Debbie Harris@Snowmass2001)

Name	Start Year	Proton Power	Proton Energy	Neutrino Energy	Baseline (km)	Years of Running	kton	$\sin^2 \theta_{13}$ (3 $\sigma$ )	CP phase $\theta$ (3 $\sigma$ )
JHF to SuperK	2008?	0.77 MW	50GeV	0.7GeV	350km	5 yrs $\square$	50	0.016	none
JHF to HyperK	2013?	4MW	50GeV	0.7GeV	350km	2 yrs $\square$ 6 yrs $\boxminus$	1000	0.0025	$\square$ 15 $^\circ$
CERN to UNO	$\geq$ 2011	4MW	2.2GeV	250MeV	130km	2 yrs $\square$ 10 yrs $\boxminus$	400	0.0025	$\square$ 40 $^\circ$

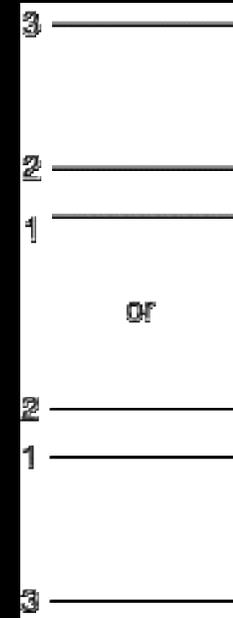
# High-energy superbeam

- Higher  $E$ , longer  $L$   $\square$  Can study matter effect to determine the mass hierarchy

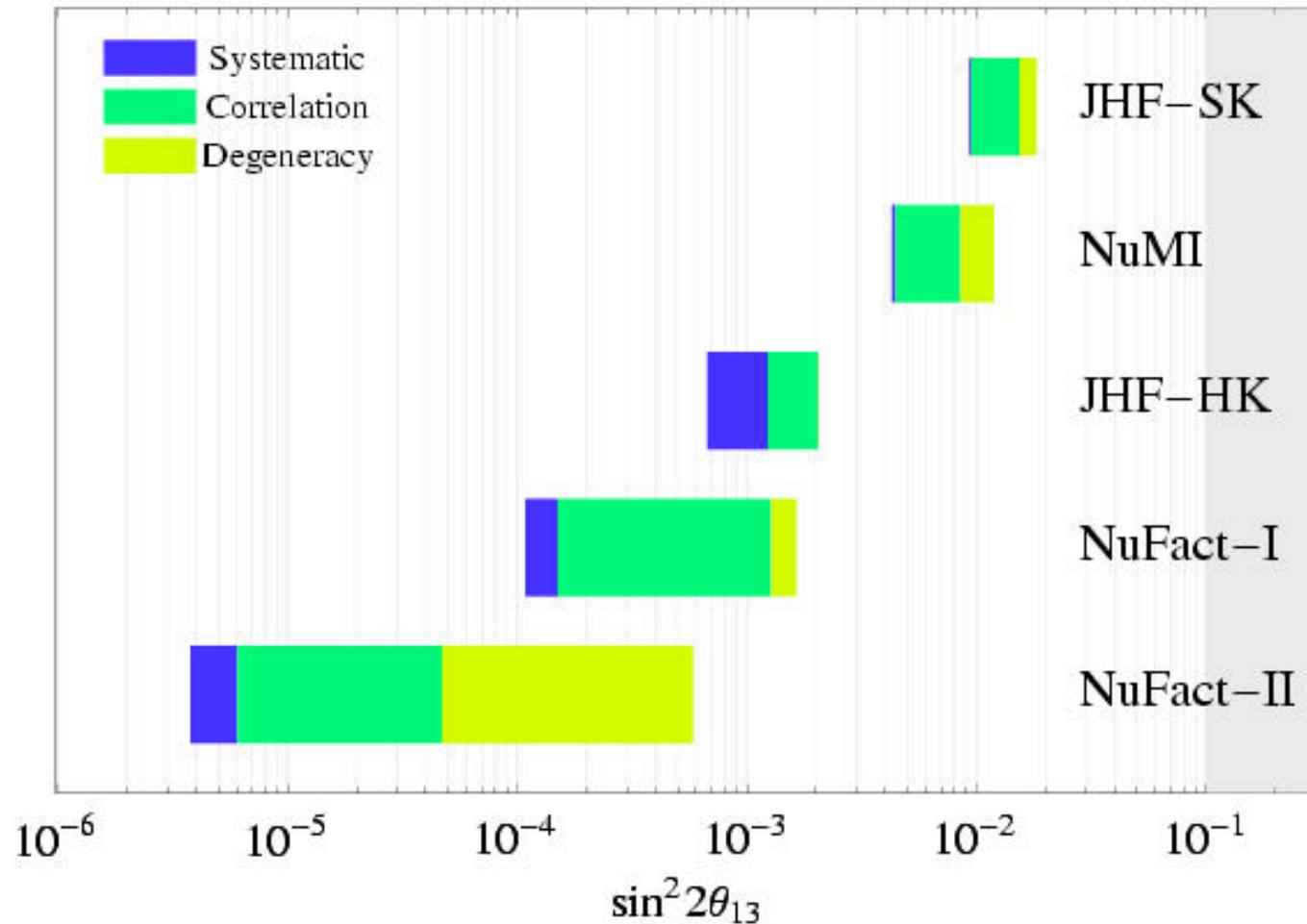
(Barger, Marfatia, Whisnant@Snowmass2001)

Baseline (km)	Neutrino Energy (GeV)	$\sin^2 \theta_{13}$ Reach ( $3\sigma$ )		Sign ( $\Delta m_{23}^2$ )	CP phase $\delta$ ( $3\sigma$ )
		$\square$	$\square \square$ bar		
350	1	.0013	.0016	–	20
730	2.1	.0017	.0026	–	24
1290	3.7	.0020	.0052	.04	32
1770	5	.0022	.0092	.02	40
2900	8.2	.0025	.037	.01	76

LBNL Hitoshi Murayama

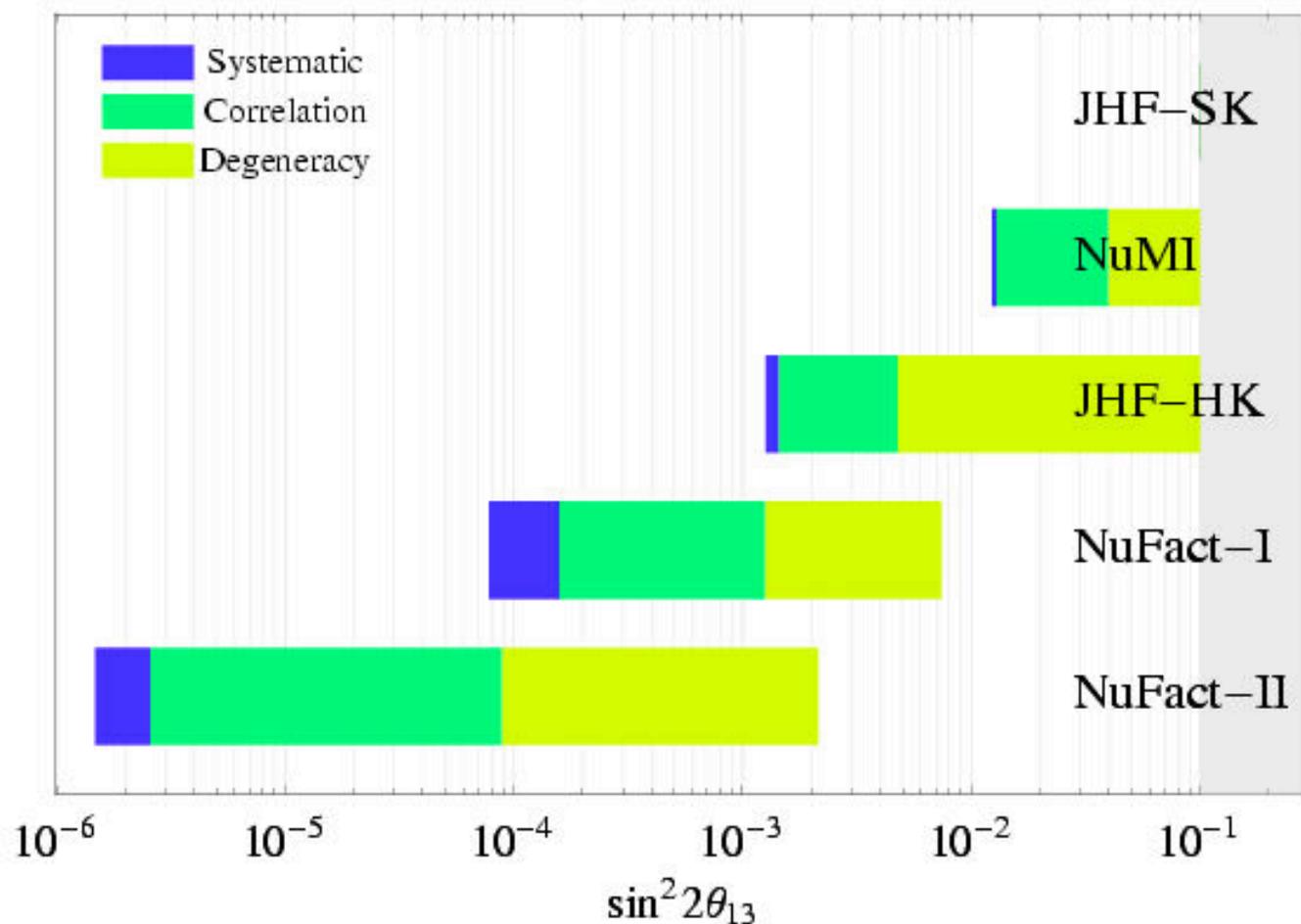


### Sensitivity to $\sin^2 2\theta_{13}$



- Different sensitivity reductions by systematics
- Correlations & degeneracies lead to severe limitations
- Improvements by combining experiments

## Sensitivity to the sign of $\Delta m_{31}^2$

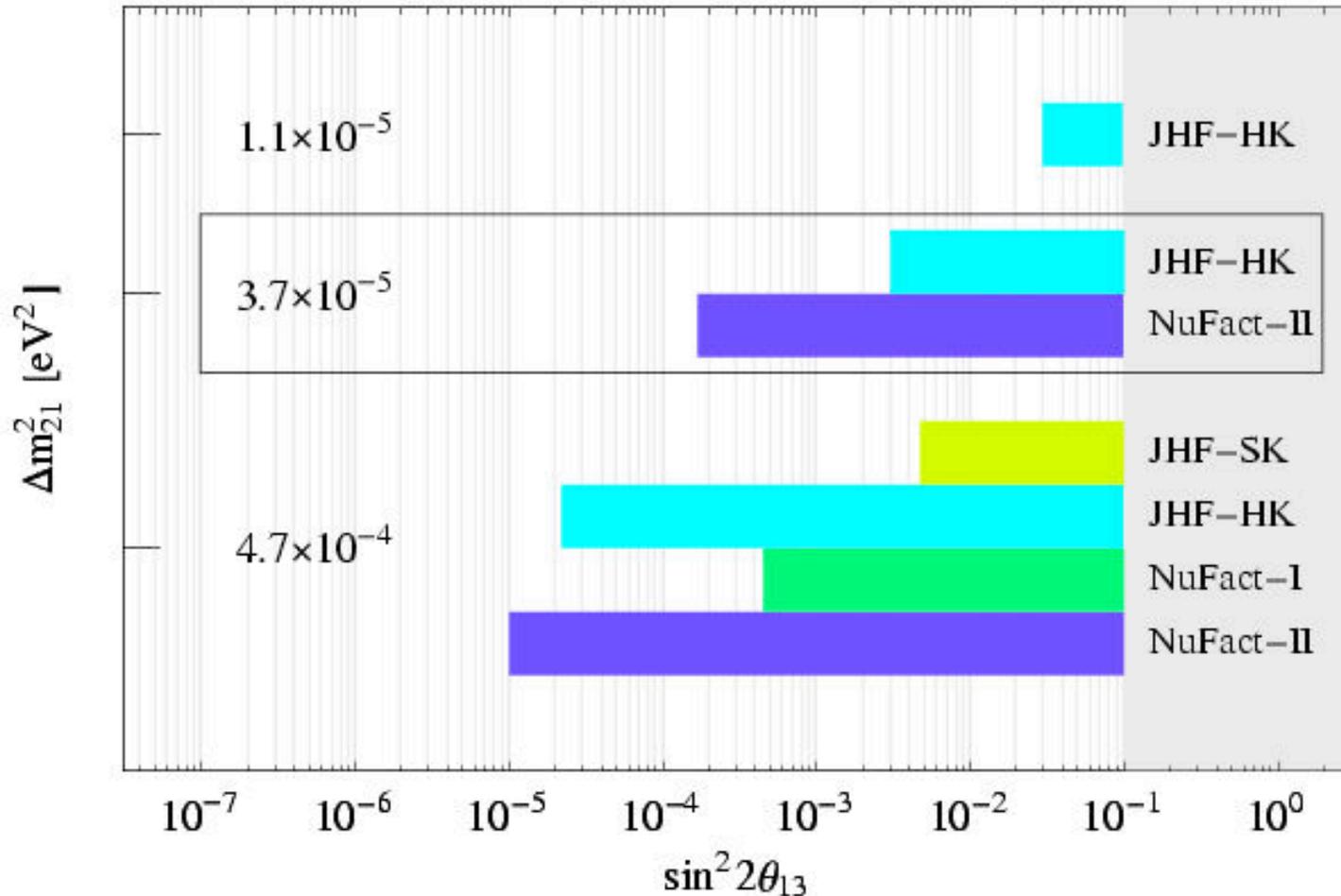


- $sign(\Delta m_{31}^2)$  very hard to determine with superbeams
- **degeneracies with  $\delta_{CP}$**  are the main problem
- ⇒ **combine experiments!**

Huber, ML, Winter, hep-ph/020435!

# Measurements of CP-violation

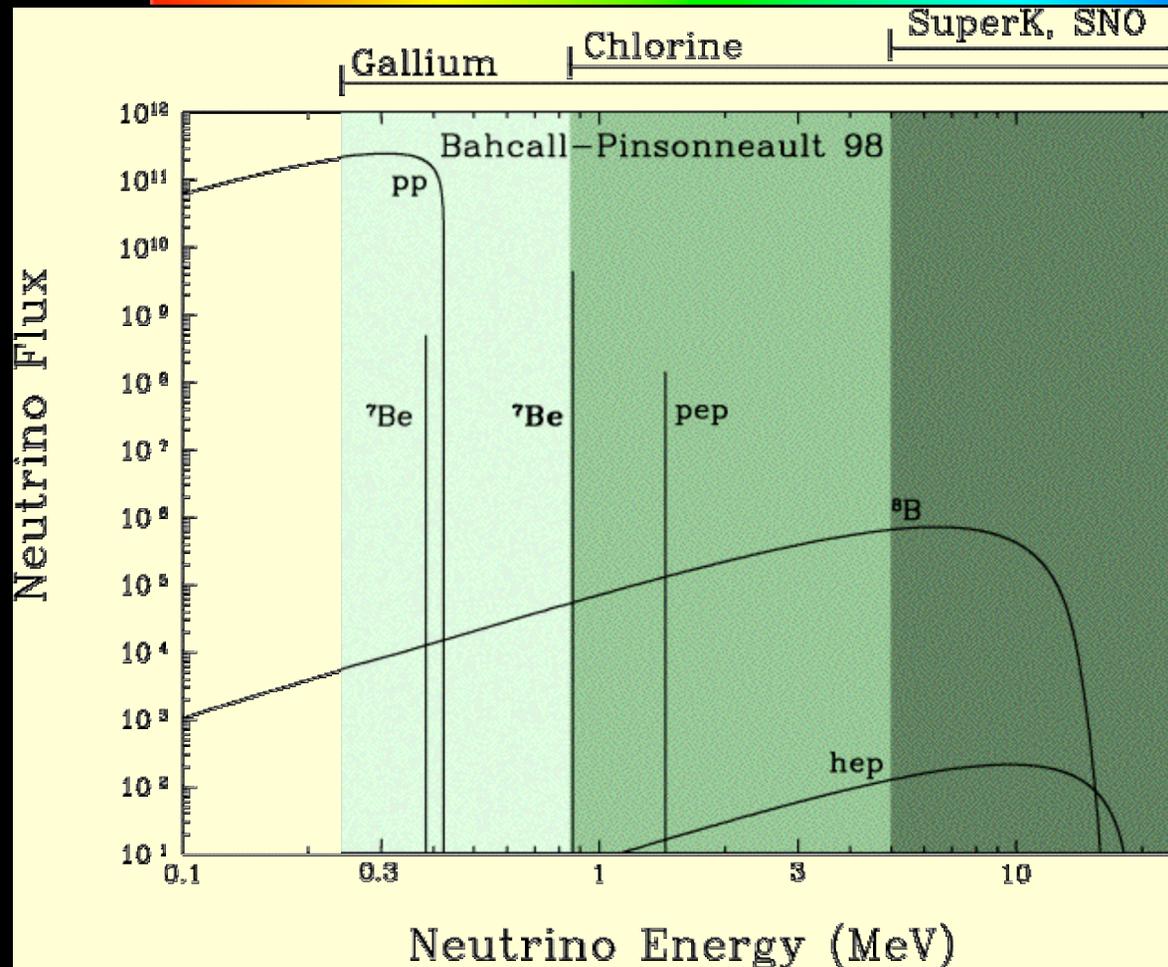
Sensitivity to CP-Violation at  $\delta_{CP} = +\pi/2$



- **CP violation** with high luminosity superbeams **feasible**
- **sensitivity is  $\delta_{CP}$  dependent**

Huber, ML, Winter, hep-ph/0204351

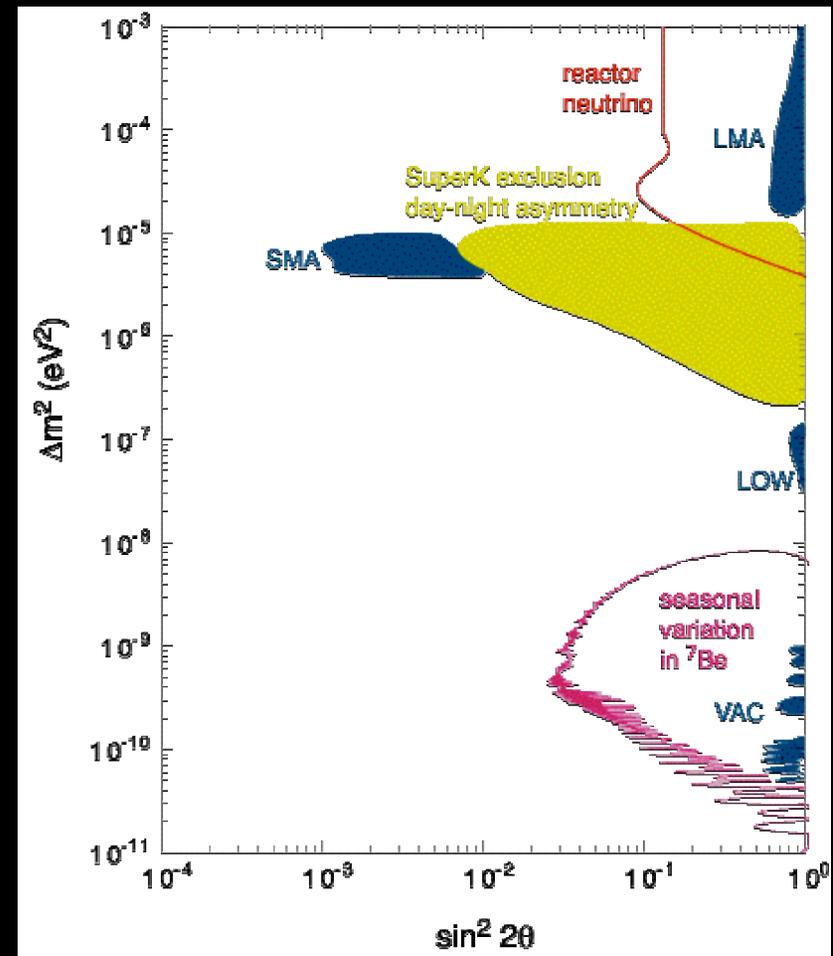
# Solar Neutrino Spectrum



Bahcall-  
Pinsonneault

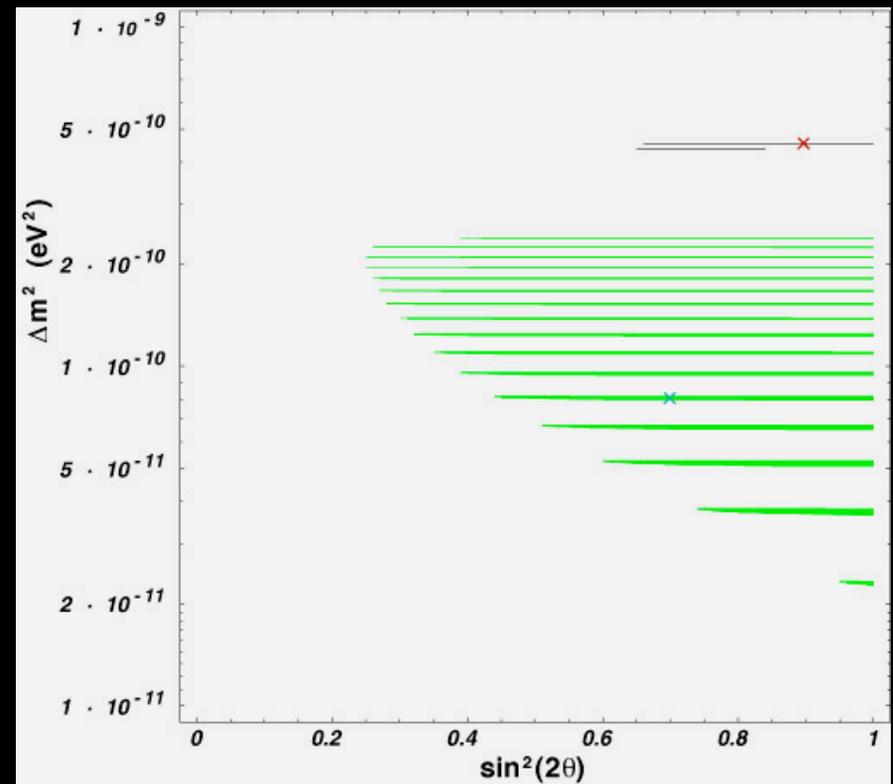
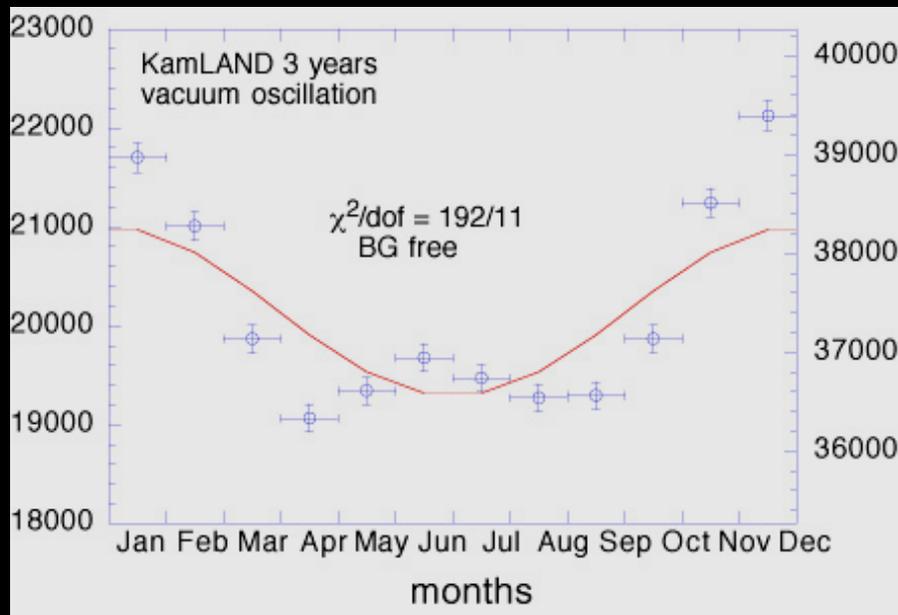
# *VAC by seasonal variation*

- ${}^7\text{Be}$  neutrino monochromatic
- seasonal effect probes VAC region  
(de Gouvêa, Friedland, HM)
- Borexino crucial
- Hopefully also by KamLAND



# VAC by seasonal variation

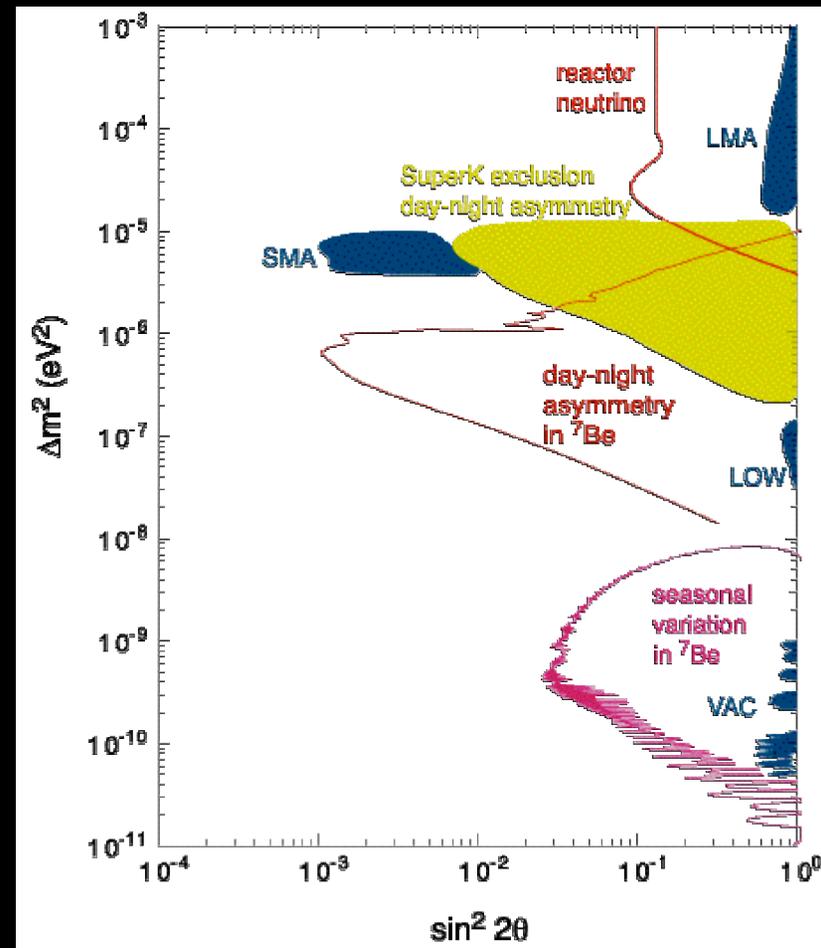
- Fit to seasonal variation to measure parameters



Can pep  $\square$  resolve degeneracy?

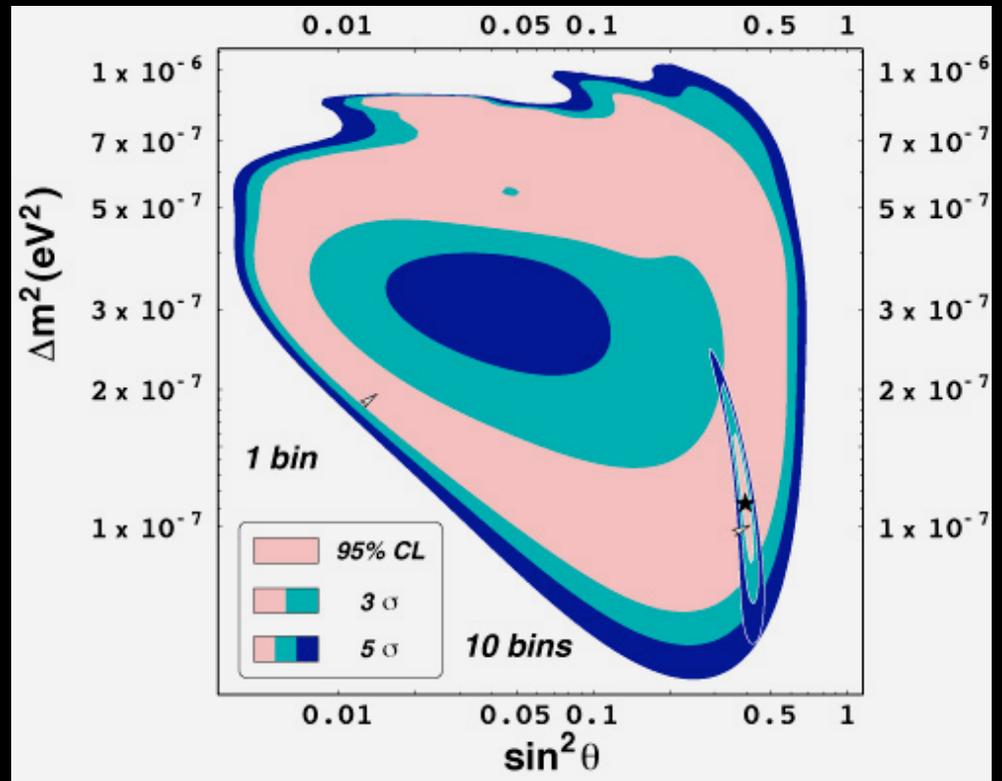
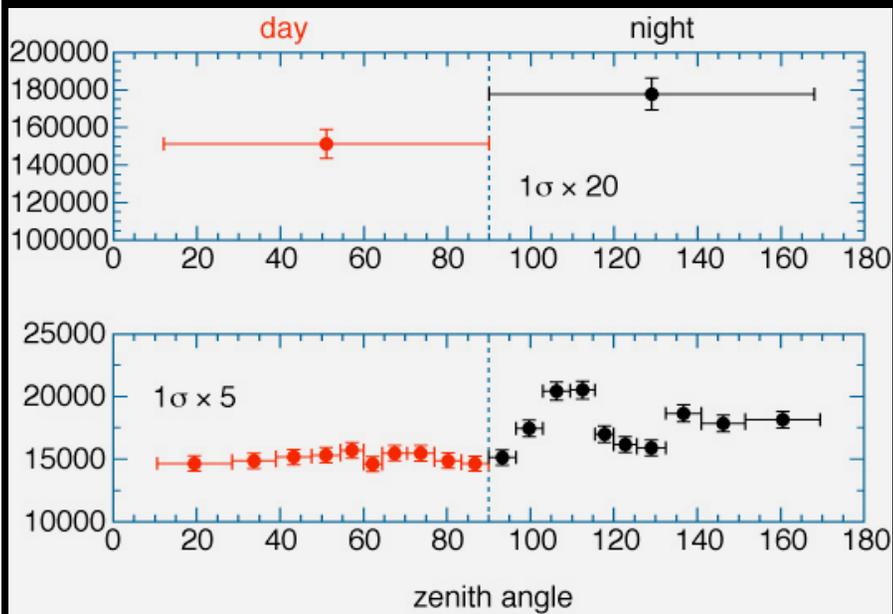
# *LOW by day/night effect*

- ${}^7\text{Be}$  neutrino monochromatic
- Day/night effect probes LOW region
- (de Gouvêa, Friedland, HM)
- Borexino crucial
- Hopefully also by KamLAND



# *LOW by zenith angle dependence*

- More information in zenith angle depend.  
(de Gouvêa, Friedland, HM)



# Flavor Content

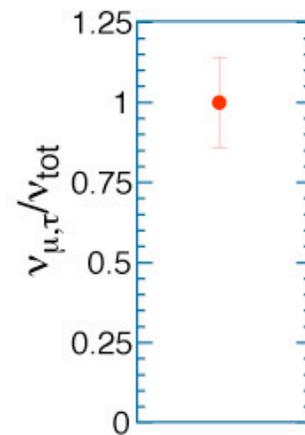
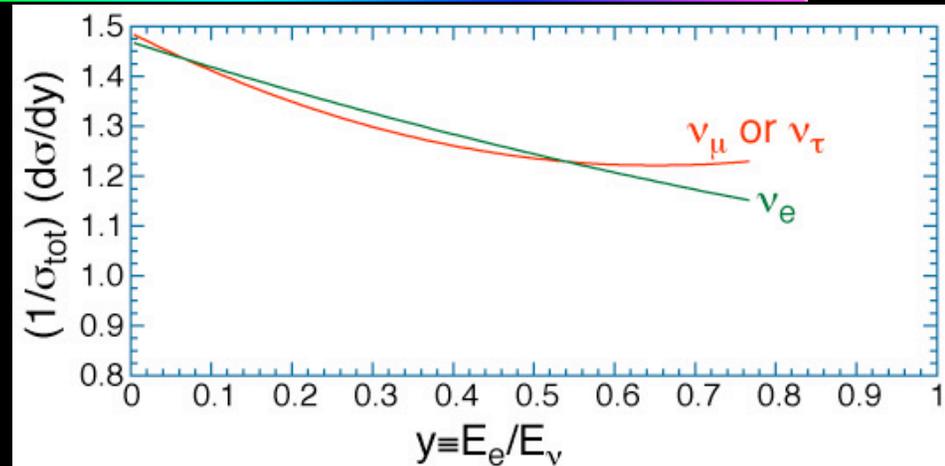
- Small difference in recoil spectrum

NC:  $e^- \bar{\nu}_{\mu, \tau} \nu_{\mu, \tau}$   $e^- \bar{\nu}_{\mu, \tau} \nu_{\mu, \tau}$

NC+CC:  $e^- \bar{\nu}_e \nu_e$   $e^- \bar{\nu}_e \nu_e$

- Can in principle be used to discriminate flavor of solar neutrinos model-independently

(de Gouvêa, HM)



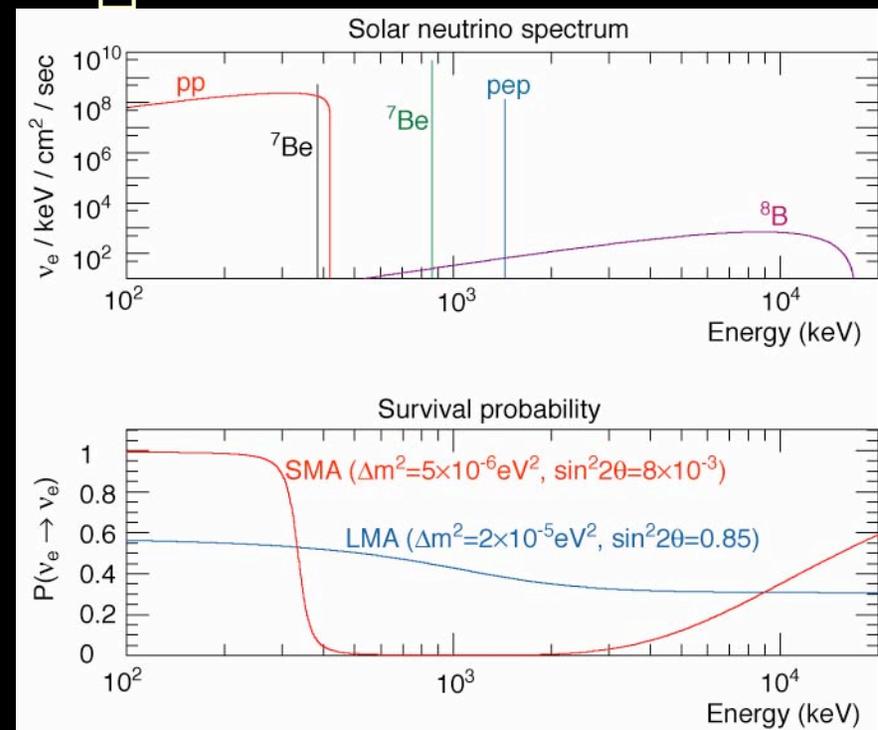
${}^7\text{Be}$   
SMA  
KamLAND  
600t\*3yrs

# SMA by pp neutrinos

- SMA: Sharp falloff in probability in the pp neutrino region the survival
- Because of the condition for the level crossing

$$\frac{\Delta m^2}{2E} < \sqrt{2}G_F n_e(0)$$

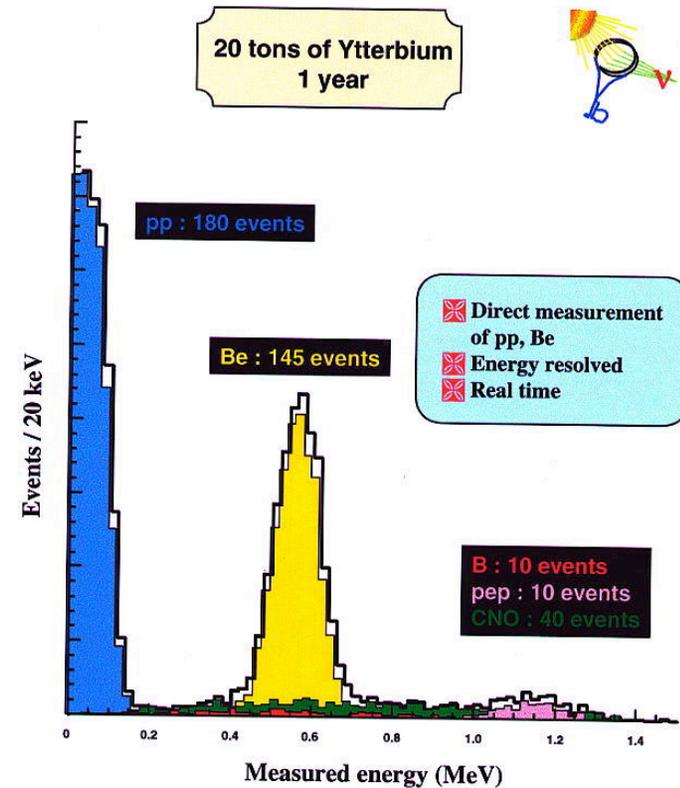
- Measure the falloff  $\Delta m^2$  measurement



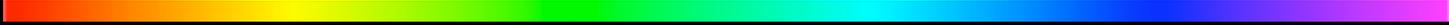
# Can $pp$ neutrinos be studied?

- CC+NC (electron recoil)
  - gaseous He TPC
  - HERON: superfluid He (phonon & roton)
  - liquid Xe
  - GENIUS: Ge
- CC ( $\bar{\nu}_e$  capture)
  - LENS: Yb or In
  - MOON: Mo

## LENS-Yb



# *Case for low-energy solar $\theta$ ?*



- If KamLAND disproves LMA, case for low-energy solar  $\theta$  is very clear:
  - Settle solar neutrino problem!*
- What if KamLAND proves LMA?
  - Unitarity test using  $pp$  flux (“known” better than 1%) to study possible sterile contribution
  - Precision measurement of  $\theta_{12}$  using  $P_{\text{surv}} = \cos^2 \theta_{12}$  for  $pp$  and  $P_{\text{surv}} = \sin^2 \theta_{12}$  for  ${}^8\text{B}$
  - Testing solar astrophysics
  - Too much work?

# *Case for neutrino superbeam?*



- If KamLAND confirms LMA, case for  $\bar{\nu}$  superbeam is very clear:

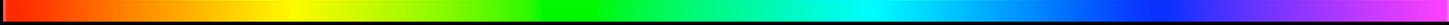
*Find CP violation!*

- What if KamLAND disproves LMA?
  - $\sin^2 2\theta_{13}$
  - $\text{sign}(\Delta m^2_{23})$
  - Consistency check with mode  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
  - Too expensive?

*Future*  
– *LSND true* –

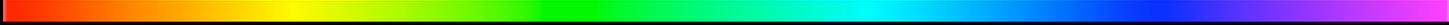


# *The hell breaks loose*



- Sterile neutrinos?
  - How many of them? 3?
  - Even with just one, there are six angles, three phases, four masses to determine
- “Short” baseline experiments ( $\sim 10\text{km}$ ) the initial target
  - Search for various oscillation modes with  $\Delta m^2_{\text{LSND}} \sim 0.1 - 1 \text{ eV}^2$

# *The hell breaks loose*

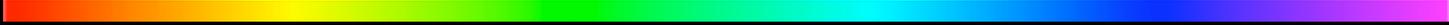


- CPT Violation?
  - Determination of three angles, one phase, two mass-squared differences for neutrinos and anti-neutrinos separately
  - Combination of “short” and “long” baseline experiments together with low-energy solar neutrino experiments

# *Absolute Mass Scale*



# *Cosmology vs Direct Mass Meas.*



- Combination of
  - CMBR anisotropy power spectrum (MAP/Planck)
  - Sloan Digital Sky Survey
  - Sensitive down to  $\sum m_{\nu} \sim 0.3$  eV
- Tritium end point
  - KATRIN
  - $m_{\nu} \sim 0.35$  eV
- Both approaches require three “degenerate” neutrinos
  - Most theorists think unlikely...

# *Majorana vs Dirac*

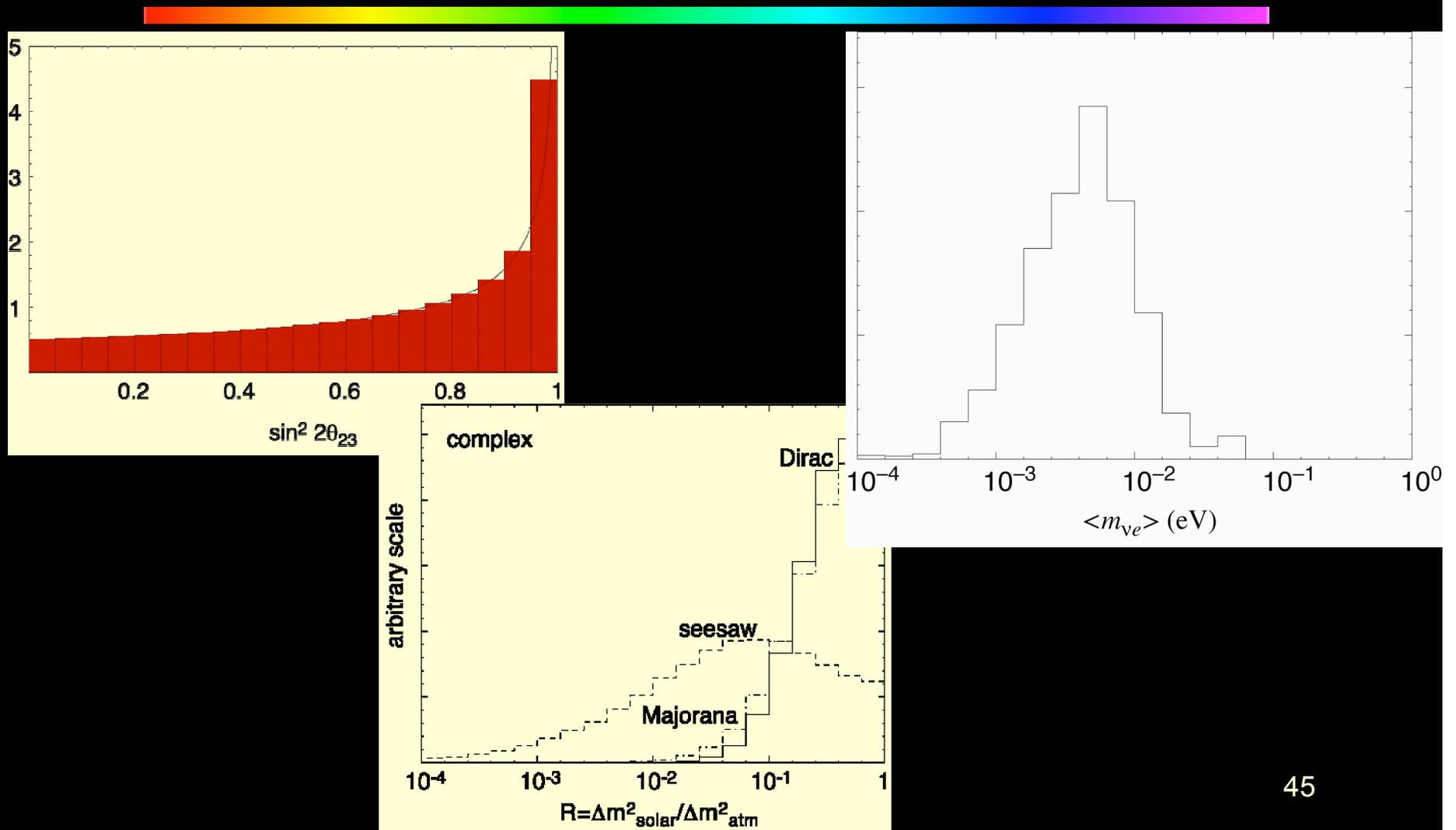


# Neutrinoless Double-beta Decay

- The only known practical approach to discriminate Majorana vs Dirac neutrinos
- $0\nu\nu\nu$ :  $nn \rightarrow ppe^-e^-$  with no neutrinos
- Matrix element  $\mu \langle m_{\square e} \rangle = \sum_i m_{\square i} U_{ei}^2$
- $m_3 \sim (\sum m_{23}^2)^{1/2} \approx 5 \times 10^{-2} \text{eV}$  looks promising
- However  $m_3 U_{e3}^2 \ll m_3$
- Upside down hierarchy an easier target
- Still cancellation between  $m_1$  and  $m_2$  possible if  $U_{e1}^2$  and  $U_{e2}^2$  destructively interfere

# Random $3 \times 3$ seesaw “Anarchy”

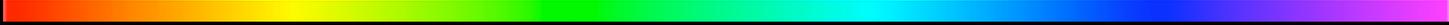
(Hall, HM, Weiner; Haba, HM)



# “Best Case” Scenario

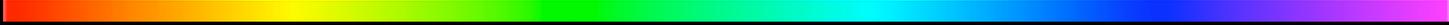
- Suppose finite neutrino mass found with Tritium end point
  - say, all three  
 $m_{\nu_i} \sim 0.5 \text{eV}$
- Suppose  $0 < \theta_{12} < \pi/4$  found
- Determine  $\theta_{12}$  from  $pp$  solar neutrino precisely
  - If
    - $|\langle m_{\nu_e} \rangle| = |\sum_i m_{\nu_i} U_{ei}^2| < m_{\nu_i}$   
 but  
 $|\langle m_{\nu_e} \rangle| > m_{\nu_i} \cos 2\theta_{12}$ ,
    - it demonstrates the need for a Majorana phase
      - Leptogenesis?
  - Uncertainly in nuclear matrix element likely limiting factor ( $\sim 2$ ?)

# Conclusions



- LSND false, LMA true
  - $\Delta_{13}$  and CP violation using superbeam,  $\bar{\nu}$ -factory?
- LSND false, LMA false
  - low-energy solar neutrino
- LSND true
  - Combination of “short” and “long” baselines, solar neutrinos
- Need absolute mass determination in any case
- Need discriminate Dirac vs Majorana in any case

# General Question



- In the case of  $B$ -physics, consistency check of three-generation CKM framework tests physics beyond the standard model
- Neutrino mass itself is physics beyond the standard model
- Minimal extension: SM with massive neutrinos
- Does the consistency check of three-generation MNS framework go beyond the SM with massive neutrinos?
  - Yes on possibilities of sterile neutrino
  - What else?  $R$ -parity violation?